A method of determining the sound pressure resulting from a surface element of a sound emitting surface

Field of the invention

The invention relates to the detection and identification of sound sources, and noise sources in particular, with the purpose of reducing noise emission.

Background of the invention

Protection of the environment and human beings has become increasingly important. Buildings, vehicles such as cars, buses and aircraft, household appliances and industrial machinery have noise producing components such as engines, motors, gears, transmissions etc. In order to protect individuals from such noise, the noise generating components and the transmission path of the noise to a human being have been investigated with the purpose of reducing the generated noise at the source and of reducing the noise transmitted from the source to human beings.

Testing of acoustic properties of noise generating and noise transmitting media such as mechanical structures and air or other fluids is an important part of the process of noise reduction. In complex structures with several noise sources, such as mentioned above, it can be complicated to identify noise sources and transmission paths and their contributions to the perceived noise.

Mathematical models and computerised methods exist for vibro-acoustic analysis of physical structures. Acoustical tools exist for simulating acoustic properties of portions of a human being, such as Mouth Simulator type 4227, Ear Simulators types 4185 and 4195, Head and Torso Simulators types 4100 and 4128, all from Brüel & Kjær Sound and Vibration Measurement A/S, Denmark. All of these are intended for use in analysing sound at different

stages in its "normal" forward transmission from the source to a human being.

EP 0 015 852 discloses a three-dimensional array of microphones for measuring the total or directional acoustic power emitted by a sound source. Such an array is suitable for use with the method of the present invention.

US 2002/0035456 discloses a method for predicting the sound pressure at a point resulting from waves generated by or scattered from a body. The method uses acoustic transfer vectors and the reciprocity principle. A purely numerical reciprocal determination of acoustic transfer vectors is disclosed through simulation of a monopole point source in the listening position, numerical determination of the response at the body surface, and hence elements in the acoustic transfer vector.

The transfer function for sound from a small omni-directional sound source to a point of measurement is often expressed as the acoustic transfer function H (or acoustic transfer impedance Z_t) defined as $H = p/Q$, where Q is the volume velocity emitted from the sound source, and p is the sound pressure at the point of measurement resulting from the volume velocity Q generated by the sound source. In most cases the analysed mechanical and acoustic transmission media are reciprocal, which means that the acoustic transfer function is the same both for forward and reverse transmission. In other words, if the sound source and the measuring microphone are interchanged, whereby the transmission of sound through the media is reversed, and boundary conditions remain unchanged, then the acoustic transfer impedance is unaffected, i.e. the "forward" acoustic transfer impedance and the "reverse" acoustic transfer impedance are identical.

It is known to use this fact when analysing the transmission of sound, whereby a sound source is placed in a position that is normally occupied by a human being, i.e. a "listening" position, and a microphone is placed in the normal position of the sound source. This has distinct advantages when iden-

tifying sound sources and tracking the noise on its path from the source to the listening position.

When measuring the forward transmission path a Head and Torso Simulator type 4100 from Brüel & Kjær Sound and Vibration Measurement A/S can be placed in the listening position, whereby very realistic measurements of the forward transmission path can be obtained, since the influence of the head and the torso on the transfer function to the ears is taken into account. Danish patent application PA 200300589 discloses a simulator simulating acoustic properties of the head and possibly the torso of a human being. That simulator comprises a sound source for outputting sound signals through the simulated ears. Such a simulator completes the reverse measuring chain and can be placed in a position that is normally occupied by a human being, i.e. a "listening position". By means of a pair of microphones in each simulated ear canal the output sound volume velocity can be measured. This is useful for computing the acoustical transfer function from a sound source to a listening position.

When designing e.g. vehicles such as cars, buses and aircraft the comfort of the passengers, the driver and crewmembers is of importance. Noise can seriously jeopardize not only comfort but also the health of humans. It is therefore important to reduce noise, and for effectively reducing noise it is important to identify noise sources and their individual contribution to the noise level at locations where people are present. Mechanical structures such as body and wall panels can vibrate and emit noise, and large structures can have "hot spots" that emit more noise than "cold spots". Not all hot spots may be serious contributors to the noise level resulting at a "listening position", and, vice versa, cold spots may contribute more seriously than expected. Such phenomena can e.g. be due to conditions in the transmission path from the source to the listening position.

The problem to be solved by the invention is to provide a method of determining, in a predefined position such as a listening position of a human being, the sound pressure resulting from sound emitted from a surface element of a sound emitting surface. In particular there is a need for identifying, among the plurality of noise sources, which can be distributed over a large area, the most significant sources and their contributions to the noise level at one or more listening positions.

Summary of the invention

The invention provides such a method for determining the contribution of each surface element of a sound-emitting surface to the noise level at e.g. a listening position.

The sound pressure in the listening position resulting from the sound emitted from a surface element can be calculated by multiplying the emitted volume velocity by the acoustic transfer function (also referred to as the acoustic transfer impedance) from the surface element to the listening position. In general, the acoustic transfer function is defined as the (complex) ratio of the effective sound pressure p at a given point to the volume velocity q of the sound source generating the sound pressure p.

It is assumed that the analysed mechanical and acoustic transmission media are reciprocal, which means that the acoustic transfer function is the same both for forward and reverse transmission. The acoustic transfer function can advantageously be found as the "reverse" acoustic transfer function.

The invention comprises the following two main phases, in which two different measurements are performed to determine the noise source strength and the transfer function, respectively.

I. An "operational measurement" is made with the noise source(s) operating under the conditions to be investigated. A three-dimensional array of micro-

phones is used to measure the three-dimensional sound field above a surface element of a sound emitting surface, and at the surface element the component of the air-particle velocity perpendicular to the surface element is calculated using e.g. Near-Field Acoustical Holography (NAH), the Statistically Optimal NAH (SONAH) as described in [2], or the Inverse BEM (Boundary Element Modelling). The volume velocity emitted by the surface element is then determined by integrating the air-particle velocity over the area of the element - or approximately as the air-particle velocity perpendicular to the surface element multiplied by the area of the surface element. Several surface elements may be covered and measured simultaneously, and the dimensions of each element should be small in comparison to the wavelength.

II. A "transfer function measurement" is made with the noise source(s) under investigation inactivated. This measurement is typically taken with the same array of microphones in the same position as in the operational measurement above, but now the surface element itself must be rigid and non-vibrating. A volume velocity sound source is used to emit a volume velocity in a listening position, and the array of microphones is used to determine the resulting three-dimensional sound field above the surface element. The sound emitted from the volume velocity sound source should preferably be the only sound or at least dominate over possible other sounds. Using e.g. Near-Field Acoustical Holography the resulting sound pressure at the surface element is determined. The acoustic transfer function between the surface element and the listening position is assumed to be reciprocal and is determined as the ratio of the resulting sound pressure at the surface element to the volume velocity emitted by the volume velocity sound source.

The sound pressure in the listening position resulting from sound emitted from the surface element is then determined as the volume velocity emitted by the surface element multiplied by the acoustic transfer function.

For each position of the microphone array 10 all the above steps are repeated, and a noise source "map" can be made of the entire interior surface of e.g. a car cabin, or important parts thereof. Such a map can be used for identifying the most serious noise sources to be attenuated.

The above-described method requires the measurement of the reciprocal transfer function to be performed with the air-particle velocity perpendicular to the surface elements equal to zero, which in turn requires that the surface elements are rigid. According to the above, the only acoustical quantities on the surface element that are taken into account are the "operational" air-particle velocity at the surface and the sound pressure resulting from the volume velocity sound source.

A more general method uses also the "operational" sound pressure and the particle velocity created by the volume velocity sound source, whereby the requirement for rigid surface elements is avoided.

Brief description of the drawings

Figure 1 is a plan view of a portion of a three-dimensional array of microphones used with the invention,

Figure 2 is a side view of the three-dimensional array of microphones in figure 1 shown in a measurement relationship to a sound-emitting surface, and

Figure 3 illustrates a measurement set-up for measuring in e.g. a car cabin.

Detailed description of the invention

The measurement set-up used in the invention is as follows.

In figures 1 and 2 a three-dimensional array 10 of a plurality of microphones M is shown. The term "microphone" is here used as the generally accepted term for a transducer that generates an (electrical) output signal in response to pressure variations in the fluid (air, water etc.) that surrounds the trans-

ducer. The array comprises two identical, parallel layers of microphones M spaced a vertical distance d_v apart. In each layer the microphones are distributed in two sets of parallel rows forming a square grid with the rows spaced horizontal distances d_{hx} and d_{hy}, respectively, apart. In the preferred embodiment shown, the vertical distance d_v and the horizontal distances d_{hx} and d_{hy} are identical, whereby the microphones are uniformly distributed and form a cubic lattice. A non-periodic or non-uniform, such as pseudo-random, distribution of the microphones can also be used. The microphones have well-defined, preferably identical, electro-acoustical properties. The array of microphones preferably has a multi-pole plug (not shown) for connecting the microphones to measuring equipment, which is not part of the invention. Each layer of the array can have e.g. 6x6 or 8x8 or any other suitable arrangement of microphones. The vertical and horizontal spacing determine the upper frequency limit at which the array can be used. A vertical and horizontal spacing of 5 cm results in an upper frequency limit of about 3 kHz.

As indicated in figure 2, the two layers are separate layers that are assembled and can be disassembled and used independent of each other. The two layers are here planar layers mounted back-to-back, but a fixed three-dimensional array may also be used.

In figure 3 is shown a rectangular frame illustrating e.g. the cabin of a car. The cabin has an interior surface S, which, due to vibrations from the engine, the tyres etc that are transmitted to the cabin, will emit corresponding sound (noise) into the cabin.

In figures 2 and 3 the three-dimensional array 10 of microphones is arranged above the surface S. A surface element ΔS of the surface S is shown beneath the microphone array 10. The position of the microphone array 10 relative to the surface element ΔS including the distance D and the lateral coordinates must be well-defined. For regular array geometry, there will typically be one surface element ΔS for each microphone (in the layer close to the

surface), with the microphone at the centre of the corresponding surface element.

With the above set-up the following measurements are taken.

First, an "operational" measurement is taken with the set-up shown in figures 2 and 3. With the "real life" noise sources (engine, tyre noise etc) active, and with the microphone array 10 in the shown position, the sound pressure at each of the microphones M is measured.

Based on the measured three-dimensional distribution of sound pressure over the array of microphones, a calculation is performed of the air-particle velocity u_n perpendicular to the surface element ΔS resulting from the sound emitted from the entire surface S. This can be done using e.g. a well-known Near-Field Acoustical Holography (NAH) method, whereby the three-dimensional acoustical near-field is extrapolated to the surface element ΔS.

Next, a "transfer function measurement" is made. A volume velocity sound source is used to emit a well-defined volume velocity at a predefined position such as a listening position, i.e. a position in which a person occupying a seat in the car would normally have his head or one of his ears. A volume velocity sound source is a sound source that has a speaker in an enclosure with an orifice through which the speaker emits sound with a well-defined volume velocity. The output volume velocity can be measured or calculated by well-known methods, or the volume velocity sound source can be calibrated to emit a volume velocity that is known due to calibration.

The preferred volume velocity sound source 11 is the one disclosed in Danish patent application PA 200300589, which is a simulator simulating acoustic properties of the head and the torso of a human being. The simulator has a sound source for outputting well-defined volume velocity sound signals through the simulated ears for reciprocal measurement of the transfer impedance from a source position to one of the simulated ears.

The noise sources, the engine etc., are switched off, and the volume velocity sound source 11 is used as at least the dominating sound source and preferably the only sound source to avoid possible influence from other sound sources. With the three-dimensional array of microphones still in a predefined position (preferably the same as above) relative to the surface element, the sound pressure at each of the microphones, i.e. the three-dimensional distribution of sound pressure over the array of microphones, is again measured. Using e.g. a Near-Field Acoustical Holography (NAH) method, the three-dimensional distribution of sound pressure over the array of microphones, i.e. the acoustical near-field is extrapolated to calculate the sound pressure on the surface element ΔS resulting from the sound emitted by the volume velocity sound source.

The transfer function is then calculated as the ratio of the calculated sound pressure at the surface element to the volume velocity emitted from the volume velocity sound source. The thus calculated transfer function is both the reverse transfer function and the forward transfer function.

With the volume velocity emitted by the surface element and the transfer function both being known, the resulting sound pressure at the listening position can be found by multiplying the volume velocity by the transfer function.

Depending e.g. on the size of the microphone array 10 and the size of the surface element ΔS, measurement and calculation of the sound pressure resulting from one or more surface elements ΔS can be performed with one position of the microphone array 10. If the contributions from several surface elements are calculated, then these can be added to obtain the contributions from larger areas.

The above-described method requires that the air-particle velocity u_n perpendicular to the surface element ΔS is zero when measuring the transfer function. This requirement is only fully satisfied when the surface S is rigid. In

case of a car cabin the interior surfaces often have sound attenuating or sound absorbing materials, which are not rigid, or such materials delimit the useful space of the cabin.

The more general version of the method of the invention to be described below is not limited to rigid surfaces, but the surfaces can be soft such as sound attenuating or absorbing materials. On soft materials the air-particle velocity u_n perpendicular to the surface element ΔS is not necessarily zero when measuring the transfer function, i.e. with sound emitted from a volume velocity sound source. In the more general version of the method of the invention the same measurements as described above are taken, but the processing of the measurements is slightly extended with more calculations.

Like above described, an "operational" measurement is taken with the set-up shown in figures 2 and 3. With the noise sources (engine, tyre noise etc) active, and with the microphone array 10 in the shown position, the sound pressure at each of the microphones M is measured. In addition to the calculation of the air-particle velocity u_n perpendicular to the surface element ΔS resulting from the sound emitted from the surface element, the sound pressure p on the surface element ΔS is also calculated. This, too, can be done using e.g. a well-known Near-Field Acoustical Holography (NAH) method.

Further, also a "transfer function measurement" is made. This is done with the set-up shown in figure 3. In addition to the calculation of the sound pressure p_V on the surface element ΔS resulting from the sound emitted by the volume velocity sound source, the air-particle velocity $u_{V,n}$ perpendicular to the surface element ΔS resulting from the sound emitted by the volume velocity sound source is also calculated. This, too, can be done using e.g. a well-known Near-Field Acoustical Holography (NAH) method.

The sound pressure Δp at the listening position is then calculated using the following formula

$$\Delta p = \iint_{\Delta S} \left[\frac{p_V}{Q_V} u_n - \frac{u_{V,n}}{Q_V} p \right] dS \qquad (1)$$

where Q_V is the volume velocity emitted by the volume velocity sound source.

For practical purposes, when the variations in sound pressure and particle velocity over the surface element ΔS are small and can be regarded as constant, the surface integral in the above formula (1) can be calculated using the following more simple formula

$$\Delta p = \left[\frac{p_V}{Q_V} u_n - \frac{u_{V,n}}{Q_V} p \right] \Delta S \qquad (2)$$

The method of the invention is not restricted to closed volumes such as a car cabin, but can also be used for determining the sound pressure resulting from virtually any distributed sound source such as large machinery or a plurality of machines.

The surface element ΔS needs not be the vibrating surface of a mechanical device but can be any imaginary surface in an acoustic medium such as air, or the surface element ΔS may include or be part of a sound-emitting opening in a mechanical device.

Instead of using pressure sensitive microphones as in the above-described embodiment of the invention it is possible to use particle velocity sensors or a combination of pressure sensitive microphones and particle velocity sensors. Particle velocity sensors can be arranged in a three dimensional array like the one illustrated in figures 1 and 2.

In an advantageous alternative each pressure sensitive microphone is combined with a particle velocity sensor, whereby sound pressure and particle velocity are measured substantially in the same point. This allows the thus

combined transducers to be arranged in a single layer, which is more compact than the array with two layers in figures 1 and 2.